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Physical Cropland Requirements for Nutritional Replacement of Animal-Source Foods in India A Production-Based Six-Crop Assessment Using Primary Product Allocation

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***Abstract*—Agricultural land comparisons between animal-source foods and plant foods can produce substantially different results depending on the functional unit, system boundary, treatment of co-products, yield basis, and distinction between annual cropped activity and physical land. This study evaluates the agricultural production requirement for replacing the nutritional contribution represented by India's 2024–25 production of milk, eggs, meat, and fish/seafood with a defined six-crop whole-plant production system. The analysis begins with observed production rather than a newly prescribed population diet. The study baseline represents approximately 247.87 million tonnes of milk, 149.11 billion eggs, 10.50 million tonnes of meat, and 19.775 million tonnes of fish/seafood, corresponding to 16.1276569 million tonnes (MMT) of apparent protein per year. A working mixed-diet DIAAS calculation yields a protein-equivalent target of 15.865717567 MMT/year. Replacement production is restricted to soybean, groundnut, chickpea, pigeon pea, green gram, and black gram and is evaluated through five predefined crop portfolios. The model propagates nutritional demand through usable crop output, post-production losses, crop yields, Gross Cropped Area (GCA), and physical-land conversion using India's provisional 2022–23 cropping intensity of 155.85%.**

For the Indian Mix scenario, the current propagated model reports 186.787559 Mha/year of GCA and 119.850856 Mha of physical land before the conditional fodder-land offset. Applying the study's single 6.386 Mha conditional offset produces 113.464856 Mha of residual physical land, approximately 28.037776 crore acres. At the study-defined 180% cropping-intensity sensitivity, the corresponding residual is 97.384866 Mha, or 24.064324 crore acres. The five crop portfolios demonstrate material trade-offs among land, water, nutrient, electricity, and greenhouse-gas requirements. The study does not interpret modeled land requirement as land acquisition, does not rank dietary systems, and does not establish universal nutritional adequacy. Its principal methodological contribution is the explicit use of Primary Product Allocation (PPA) to distinguish agricultural production purpose from downstream use of crop co-products. Results should be interpreted as scenario outputs under defined system conditions, with formal nutritional validation and regional agronomic analysis identified as priorities for further research.

***Index Terms*—animal-source foods; cropland; nutritional equivalence; DIAAS; Primary Product Allocation; cropping intensity; India; agricultural systems**

I. INTRODUCTION

Agricultural land is frequently discussed through simplified food-conversion narratives. One common formulation is that animals consume plant material and return a smaller quantity of edible animal product; therefore, redirecting crops to direct human consumption should release agricultural land. Such reasoning can be informative, but feed conversion, food allocation, nutritional equivalence, and physical land balance are analytically distinct questions. A tonne of feed is not equivalent to a tonne of animal product, and neither is necessarily equivalent to a tonne of plant food when the comparison is intended to reproduce a nutritional function.

The present study addresses the narrower agricultural question of what production system would be required if the nutritional contribution represented by India's existing animal-source-food production were replaced by a defined whole-plant system. This framing deliberately avoids constructing a new population-wide dietary requirement. Instead, it starts with observed production and converts that output into a common nutritional target before calculating replacement crop production (Radrapu, 2026).

The study is also motivated by a second methodological problem: agricultural commodities frequently have multiple outputs. Oilseed crops, for example, generate oil and meal. Meal can be used in animal feed, but the fact that a co-product enters feed markets does not establish that animal-feed demand was the primary reason the crop was cultivated. The study therefore applies a Primary Product Allocation (PPA) perspective in which the primary agricultural production purpose is identified before downstream resource attribution. This is intended as a complementary analytical layer rather than a replacement for life-cycle assessment (LCA) or land-use research.

Research Questions

The primary research question is: If India's existing animal-source-food production were replaced by a defined whole-plant nutritional production system, would the replacement require more physical agricultural land, less physical agricultural land, or approximately the same amount? A secondary question asks how the physical-land requirement changes when annual Gross Cropped Area is converted using India's current cropping intensity and a higher study-defined sensitivity.

Analytical Boundary

The analysis covers milk, eggs, meat, and fish/seafood as the animal-source-food baseline and six plant crops as the replacement system. It focuses quantitatively on protein-quality-weighted replacement and associated agricultural resources. It does not claim complete equivalence across all vitamins, minerals, fatty acids, bioactive compounds, or individual nutritional requirements. It also does not treat all livestock feed as human-edible or all pasture as interchangeable with cropland. These boundaries are essential because published land-use estimates differ substantially according to whether pasture, cropland, residues, co-products, and feed materials are aggregated or separated (Mottet et al., 2017; Poore & Nemecek, 2018).

II. METHOD

Production Baseline

The study uses India's 2024–25 production baseline of approximately 247.87 million tonnes of milk, 149.11 billion eggs, 10.50 million tonnes of meat, and 19.775 million tonnes of fish/seafood. These quantities are converted using the study's specified food-composition coefficients, drawing principally on Indian Food Composition Tables (Longvah et al., 2017) and government production statistics. The resulting apparent protein quantity is 16.1276569 MMT/year.

Nutritional Functional Unit

The working nutritional functional unit is annual protein-quality-weighted nutritional production equivalence represented by the specified 2024–25 animal-source-food production streams. The study implements a mixed-diet DIAAS calculation using amino-acid-specific composition and true-ileal-digestibility inputs under a selected FAO reference pattern. The resulting animal baseline mixed-diet DIAAS is 0.9837583764, yielding a protein-equivalent target of 15.865717567 MMT/year. DIAAS is a protein-quality measure based on digestible indispensable amino acids and the limiting amino-acid ratio, rather than a mechanism for creating additional protein mass (Food and Agriculture Organization of the United Nations [FAO], 2013).

The manuscript explicitly retains uncertainty around category-median digestibility harmonisation, food-form matching, and a black-gram tryptophan digestibility data gap. Consequently, 15.865717567 MMT/year is treated as the study's working target rather than as a universal biological constant. This distinction is important for reproducibility and prevents the numerical result from being presented with more certainty than the input data support.

Replacement Crop System

The replacement system consists of soybean, groundnut, chickpea, pigeon pea, green gram, and black gram. Five predefined crop portfolios are evaluated: Soy Dominant, Equal Crop Mix, Soy Balanced, Near Indian Mix, and Indian Mix. The crop shares differ among scenarios while the nutritional target remains fixed. The scenarios are analytical constructs and are not proposed as national crop policy.

Scenario	Soybean	Groundnut	Chickpea	Pigeon pea	Green gram	Black gram
Soy Dominant	50%	10%	10%	10%	10%	10%
Equal Crop Mix	≈16.7%	≈16.7%	≈16.7%	≈16.7%	≈16.7%	≈16.7%
Soy Balanced	35%	10%	15%	15%	15%	10%
Near Indian Mix	20%	20%	15%	15%	15%	15%
Indian Mix	10%	20%	20%	15%	20%	15%

Yield Basis and Production Propagation

The final crop-area calculation uses the study's five-year Indian yield basis: soybean 1,070.8 kg/ha; groundnut 1,958.2 kg/ha; chickpea 1,198.8 kg/ha; pigeon pea 847.8 kg/ha; green gram 630.2 kg/ha; and black gram 632.0 kg/ha. The calculation proceeds from nutritional target to usable crop output, applies crop-specific post-production losses, divides the resulting harvest requirement by crop-specific yield, and sums crop areas to obtain GCA.

Seed retention is treated as a separate agricultural input rather than being classified as post-production loss. This prevents the same material flow from being deducted twice and preserves the distinction between edible output, harvest requirement, and biological inputs to subsequent crop production.

III. LAND ACCOUNTING FRAMEWORK

Gross Cropped Area Versus Physical Land

A central feature of the model is the distinction between Gross Cropped Area and physical agricultural land. A hectare cultivated twice in a year contributes two hectares to GCA but remains one hectare of physical land. The Government of India's land-use statistics define cropping intensity as the ratio of GCA to Net Sown Area. The study therefore converts annual cropped activity into physical land using Physical Land = GCA ÷ Cropping Intensity.

The provisional national cropping intensity used as the current reference is 155.85% for 2022–23. Under this reference, the Indian Mix GCA of 186.787559 Mha/year corresponds to 119.850856 Mha of physical land before the fodder offset. A study-defined 180% sensitivity reduces the corresponding physical-land requirement to 103.770866 Mha before the same conditional offset.

Dedicated Fodder-Crop Land

The Department of Animal Husbandry and Dairying's Basic Animal Husbandry Statistics 2025 reports 6.386 Mha under dedicated fodder crops in 2022–23. The study does not treat this area as one-for-one replacement cropland. Instead, it applies a conditional production-capacity offset based on the yields of the defined replacement crops. Permanent pasture and other grazing land are excluded from this crop-to-crop offset.

This treatment is intended to avoid both overstatement and double deduction. The 6.386 Mha is incorporated once as a conditional offset and is not simultaneously subtracted as raw fodder hectares and again through a separate yield adjustment. The offset should not be interpreted as proof that every fodder hectare can be converted to edible pulse or oilseed production.

Primary Product Allocation

PPA is the study's principal allocation perspective. It asks which agricultural production purpose drives cultivation and assigns the cultivation burden accordingly. This is particularly relevant to multi-output oilseeds. When a crop is cultivated primarily for an edible oil market and produces meal as a co-product that subsequently enters feed markets, the study does not automatically attribute the entire upstream crop area to animal feed. This differs from an allocation approach based primarily on downstream product use.

The PPA framework therefore separates feed use from feed-driven cropland. This distinction does not deny livestock resource use or biological conversion losses. Rather, it asks whether the upstream cultivation would occur in the absence of the downstream feed market. The distinction complements existing feed-use research showing that livestock diets contain substantial quantities of materials not currently eaten directly by humans (Mottet et al., 2017).

IV. RESULTS

Five-Scenario Land Results

The current propagated model produces substantial variation in physical-land requirement across the five predefined crop portfolios. The values below are model outputs at the 155.85% cropping-intensity reference and before the conditional fodder offset.

Scenario	GCA (Mha/yr)	Physical land before offset (Mha)	Electricity (TWh/yr)	N (MMT/yr)	P (MMT/yr)	K (MMT/yr)
Soy Dominant	119.03721 1	76.37 9346	4.34 1957	2.90 2668	5.80 5337	3.38 9306
Equal Crop Mix	178.9 0054 0	114.7 9020 9	6.06 2069	3.98 4794	7.96 9589	4.31 8612
Soy Balanced	141.7 9056 7	90.97 8869	4.81 4870	3.30 9021	6.61 8041	3.65 5599
Near Indian Mix	166.6 8815 5	106.9 5422 2	6.04 9702	3.76 1767	7.52 3533	4.20 4671
Indian Mix	186.7 8755 9	119.8 5085 6	6.45 4388	4.08 1875	8.16 3750	4.44 3668

Note. All values are scenario outputs from the study's current propagated model. They are not policy rankings.

Principal Indian Mix Result

The Indian Mix is retained as the diversified reference portfolio in the study. At 155.85% cropping intensity, it requires 186.787559 Mha/year of GCA and 119.850856 Mha of physical land before the conditional fodder offset. Applying the single 6.386 Mha offset gives 113.464856 Mha of residual physical land, equivalent to approximately 28.037776 crore acres.

The study's title expression, “18 Crore Acres,” is therefore a communication shorthand rather than the exact current numerical result of the final propagated model. The detailed V5 result is approximately 28.04 crore acres for the Indian Mix after the conditional offset. The difference is material and the article treats the detailed numerical output as authoritative.

Cropping-Intensity Sensitivity

Case	Cropping intensity	Base physical land (Mha)	Conditional offset (Mha)	Residual physical land (Mha)	Residual (crore acres)
Current official reference	155.85%	119.85 0856	6.386	113.46 4856	28.03 7776
Study defined sensitivity	180.0 %	103.77 0866	6.386	97.384 866	24.06 4324

The sensitivity demonstrates the importance of distinguishing annual cropping activity from physical land. Raising cropping intensity from the official reference to the study-defined 180% sensitivity reduces the modeled Indian Mix residual by approximately 16.08 Mha. This is a mathematical sensitivity within the model, not a forecast that India can achieve 180% cropping intensity uniformly across the relevant land base.

V. RESOURCE IMPLICATIONS AND DISCUSSION

Land Is Not the Only Resource Dimension

The model shows that changing crop composition affects several resource dimensions simultaneously. The Indian Mix has the highest physical-land requirement among the five scenarios, but crop portfolios also differ in electricity and nutrient requirements. The Soy Dominant scenario has lower modeled GCA and physical land than the Indian Mix, whereas the Equal Crop Mix has higher requirements for several resource measures. These differences demonstrate why a single environmental indicator cannot be assumed to represent the complete agricultural burden of nutritional replacement.

The study includes blue water, nitrogen, phosphorus, potassium, cultivation-related greenhouse-gas emissions, machinery-related emissions, seed requirements, labour, electricity, irrigation energy, residue generation, screening-level biogas potential, and mechanisation-related expenditure. These modules are linked to the crop-production pathway and should be interpreted as associated resource profiles rather than as a complete national LCA.

Relationship to Existing Land-Use Literature

Poore and Nemecek (2018) consolidated environmental-impact data from thousands of farms and food-system observations and demonstrated substantial variation among producers. Their work provides an important global benchmark for food-system land and environmental assessment, but the present study asks a different question: what happens when a specific nutritional output from an observed national production system is replaced using a restricted Indian crop portfolio? Differences in functional unit and allocation rule therefore matter when comparing results.

Mottet et al. (2017) similarly demonstrate why feed material must be disaggregated. Their analysis found that a large majority of global livestock feed dry matter consisted of materials not currently eaten by humans. The present study does not dispute this finding; instead, it separates human-edible feed, human-inedible feed, residues, co-products, and dedicated feed production because each category has a different opportunity cost in a land-balance calculation.

Why the Result Is Not a Universal Vegan-Diet Land Estimate

The calculated land requirement applies only to the defined replacement system. It is not an estimate of the land required for every possible whole-plant diet, nor is it a prediction of the outcome of an actual national dietary transition. The result depends on the six-crop restriction, Indian yield basis, post-production losses, nutritional target, cropping intensity, conditional fodder offset, and PPA treatment. Expanding the crop portfolio, changing yields, using different nutritional constraints, or changing the allocation rule could produce different results.

The study therefore does not establish that a plant-only system is universally more or less sustainable than a mixed system. Instead, it demonstrates that a nutritional replacement claim becomes an agricultural land-balance problem only after the replacement nutrition, production system, yield basis, losses, cropping intensity, and allocation rules have been explicitly defined.

VI. TECHNICAL INTERPRETATION

Nutritional Equivalence

Protein mass is a useful starting point but does not fully represent nutritional equivalence. The study's use of a working mixed-diet DIAAS calculation reflects the distinction between crude protein quantity and digestible indispensable amino-acid supply. FAO (2013) identifies DIAAS as a method based on digestible indispensable amino acids and the limiting reference ratio. The present study follows that architecture but retains explicit data limitations rather than filling gaps with unverified coefficients.

The replacement crop mixtures must be evaluated at the diet level rather than by simply averaging individual crop DIAAS values. Crop proportions influence the aggregated amino-acid profile and therefore the limiting amino acid. In the study's audit, sulfur amino acids remain limiting across the replacement scenarios. This reinforces the methodological point that crop diversification is nutritionally relevant as well as agriculturally relevant.

Yield and Loss Propagation

The crop-area calculation is deliberately sequential. The common nutritional target is distributed among crops according to scenario shares; crop-specific nutritional coefficients determine usable crop output; post-production losses increase the harvest requirement; crop yields convert harvest requirements into GCA; cropping intensity converts GCA into physical land; and the conditional fodder offset is applied once at the physical-land stage. This sequence makes it possible to audit how a change in any parameter propagates through the final result.

PPA and Co-Product Accounting

PPA contributes a production-purpose layer to agricultural resource accounting. Conventional LCA allocation can use mass, economic, energy, or biophysical relationships depending on the study objective. PPA instead asks what purpose caused the agricultural cultivation to occur. This is particularly important for oilseed crops, in which the food-oil pathway and animal-feed pathway are physically connected through processing.

The purpose of PPA is not to eliminate co-product allocation. It is to prevent a downstream use from automatically redefining the upstream reason for cultivation. A rigorous application should therefore disclose the primary-purpose classification, distinguish dedicated feed crops from co-products, and provide sensitivity analysis where production purpose is uncertain.

VII. STRENGTHS AND LIMITATIONS

Strengths

- The research question is explicitly defined as a production-to-land replacement problem.
- The baseline is anchored to observed 2024–25 Indian animal-source-food production rather than a newly prescribed population diet.
- The nutritional target is fixed across crop scenarios, allowing crop-mix effects to be isolated.
- Indian crop-yield coefficients are used instead of generic global yields.
- Gross Cropped Area is separated from physical agricultural land through an explicit cropping-intensity conversion.
- Post-production losses and seed retention are treated as separate production-system flows.
- Dedicated fodder land is incorporated once through a conditional offset rather than a simple hectare-for-hectare subtraction.
- PPA makes the production-driver decision explicit for multi-output crops and co-products.
- The model reports associated water, nutrient, electricity, emissions, labour, residue, and economic modules rather than relying on a single land indicator.
- The study distinguishes modeled physical-land requirement from land acquisition or land-conversion policy.

Limitations

- The working mixed-diet DIAAS result retains category-median true-ileal-digestibility harmonisation, food-form matching limitations, and a black-gram tryptophan digestibility data gap.
- The six-crop system is intentionally restricted and therefore does not represent the full Indian crop portfolio or an optimized national food system.
- National-average or national-aggregate resource coefficients conceal substantial regional variation in soils, climate, irrigation, groundwater, infrastructure, crop calendars, and markets.
- The conditional fodder offset does not establish that all fodder land is agronomically convertible to edible crops.
- N/P/K values are nutrient-application proxies and should not automatically be interpreted as commercial fertilizer tonnage.
- Land-use-change emissions depend strongly on the source land and carbon stock and therefore require geographically explicit analysis.
- The model does not forecast farmer behaviour, commodity prices, trade, policy, land acquisition, or actual dietary adoption.
- The study is not a complete life-cycle assessment and does not resolve every upstream manufacturing, transport, processing, trade, soil-carbon, or indirect land-use pathway.

Reproducibility and Future Work

The study's calculation framework is archived through the Open Science Framework (OSF) under DOI 10.17605/OSF.IO/M9G86. A reproducible release should retain the same scenario names, units, source-data register, equation compendium, decision log, sensitivity worksheets, and version history. The next scientific stage should regionalize the model to state or district level and strengthen the nutritional module using food-specific amino-acid composition and defensible amino-acid-specific digestibility inputs.

Further work should also test alternative PPA classifications where production purpose is uncertain, incorporate spatially resolved water constraints, distinguish irrigated and rainfed production, and examine whether crop rotations and seasonal constraints permit the assumed cropping-intensity changes. Such extensions would not invalidate the current model; they would define the conditions under which its national aggregate results can be translated into geographically feasible agricultural pathways.

VIII. CONCLUSION

This study evaluates a specific agricultural question: how much physical agricultural land would be associated with replacing the nutritional contribution represented by India's 2024–25 animal-source-food production through a defined six-crop whole-plant system? The calculation begins with observed production, derives a working protein-quality-weighted target, propagates that target through crop-specific production and loss coefficients, converts GCA into physical land using cropping intensity, and applies a conditional fodder-land offset.

Under the current 155.85% cropping-intensity reference, the Indian Mix scenario produces 186.787559 Mha/year of GCA and 119.850856 Mha of physical land before the conditional offset. After the single 6.386 Mha offset, the modeled residual is 113.464856 Mha, approximately 28.037776 crore acres. At the study-defined 180% cropping-intensity sensitivity, the residual becomes 97.384866 Mha, or 24.064324 crore acres.

The principal scientific implication is methodological. Nutritional replacement cannot be translated into land requirements by comparing food mass, feed mass, or dietary labels alone. The result depends on the functional unit, protein quality, crop composition, post-production losses, yield, cropping intensity, land category, and allocation rule. PPA adds an explicit production-purpose decision that is particularly relevant to multi-output oilseed systems, where a downstream feed use does not necessarily define the upstream purpose of cultivation.

The findings should therefore be read as transparent scenario outputs rather than as a prediction of national land acquisition or a prescription for dietary policy. The study does not establish that any dietary system is universally preferable. Its contribution is to make the production-to-land calculation explicit enough to be audited, challenged, refined, and geographically expanded. A stronger next-generation model should retain this transparency while adding regional agronomic constraints and fully validated nutritional data.

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